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SUMMARY

By use of a flight simulator, variation in pilot opinion and pilot tracking proficiency with longitudinal control friction in the range of 0.3 to 6.0 pounds was investigated for three representative longitudinal stability configurations and three control force gradients. The target tracked had random motion and limited amplitude. For the tests, lateral control characteristics were held constant.

The pilot opinion data indicates that light friction values were the most acceptable and that pilot opinion of a specific configuration deteriorated with increasing control friction. Higher values of control friction were tolerated with larger control force gradients. Pilot opinion indicated an optimum short period frequency which appeared to change with control force gradient.

Analysis of pilot tracking error indicates that there was no significant variation of pilot tracking proficiency with increasing control friction except for a deterioration as the pilot opinion of the configuration became unsatisfactory. Improved tracking proficiency was shown for lighter control force gradients and higher short period frequency.

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INTRODUCTION

The subject of control friction has become, in recent years, one of considerable interest. Before the advent of control boost, control systems generally had the minimum friction obtainable, with zero control friction considered optimum but not attainable. In the present generation of aircraft with boosted control systems, in which the pilot actuates a small device which in turn actuates the control surface, near zero control frictions becomes a possibility. This investigation was conducted to examine the effect of light control friction and to, perhaps, find an optimum value within the light friction range.

It is generally recognized that pilot opinion is one of the most significant measures of the relative merit of an airplane. Many factors affecting the stability and controllability of an aircraft can be expressed quantitatively; others cannot. The merit of an airplane, which should result from weighing and summing of all these factors, almost certainly defies quantitative representation. However, in expressing his opinion of a configuration, the pilot, consciously or otherwise, performs this weighing and summing. An aircraft considered poor by pilots is not likely to be successful however good its quantitative representation may indicate. The fact that a number of the quantitative minima in effect today were originally fixed by pilot opinion makes this point particularly obvious.

In view of the foregoing, it was decided to establish a standard tracking task of a target disturbed by a random noise of limited amplitude and to record both pilot tracking proficiency and pilot opinion for a number

of aircraft configurations. These configurations include a range of longitudinal control friction, longitudinal control force gradient, and short period frequency.

A flight simulator was employed for this investigation. A simulator cannot include all of the factors that can influence a pilot's opinion or reaction; therefore, the results of this investigation must be considered limited to the degree of simulation attained. The principal lack in the flight simulator used is the absence of motion stimuli. It is believed, however, that the simulator can effectively reflect the same important trends that would be found in a similar flight situation. Another Princeton study is attempting to establish a correlation between simulator and flight data for the tracking task.

EQUIPMENT AND PROCEDURE

Equipment

The flight simulator used in these tests is shown in schematic form in Figure 1. It consisted of a pilot seated in a fixed, hooded cockpit, an electronic analog computer, associated electronic and electrical equipment, and devices for recording test data.

The pilot used as a test subject is a naval aviator with six years experience in propeller and jet fighter aircraft. Immediately prior to this investigation, he had also completed an approximately twenty-five hours test program in the same flight simulator. A few test runs were duplicated by another naval aviator of similar experience.

The hooded cockpit was fixed so that no sensations of flight were experienced by the test subject other than the feel of the controls, the motion of the reference horizon, and such as could be imagined. The cockpit was equipped with a standard aircraft seat, a control wheel appropriately mounted, and a modified dual-beam oscilliscope providing a reference horizon

and the target pip: sighting cross-hairs were scribed on a transparent overlay. This presentation is illustrated in Figure 2.

The control wheel was in the form of a simple beam extending through the hub with a hand grip at each end. Two full-bridge strain gage networks were so mounted that longitudinal and lateral control forces might be measured independently. Calibrated Sanborn Model 140 Strain Gage Amplifiers were used for this purpose. The control wheel was directly coupled to a mechanism which provided control force gradients and a means of adjusting coulomb friction forces from near zero to any desired value. Typical control force versus displacement curves are presented in Figures 3 and 4. Control displacements were limited to about plus and minus 1.15 inches longitudinally and 49 degrees right and left laterally. Potentiometer pick-off of longitudinal and lateral control displacements provided a means of recording these values and gave an electrical input to the analog computer.

The computer used was the Goodyear Aircraft Corporation Model L3 (GEDA) linear electronic differential analyzer. The computer output values were θ , ϕ , and ψ as well as their rates, which were required for the servomechanism circuits. The computer and servo outputs were summed to provide target and horizon position voltages at the oscilliscope input terminals.

Target motion for the tracking task was generated by a cam and follower device with a cam wheel for each of x and y noise. The noise signal was random, had gaussian distribution, and a maximum frequency of about one radian per second. The vector sum of the x and y noise had a maximum amplitude of 105 mils and a mean amplitude of 44 mils. The period of the cam was 133 seconds. Within these limitations, the target moved, in response to the noise signal, about a zero reference point on the horizon.

The x and y components of tracking error, ε_x and ε_y ; noise signal, N_x and N_y ; and the control displacements, δ_e and δ_a were recorded on magnetic tape in pulse width modulated form using the time division multiplexer and electronic coder sections of an Applied Science Corporation of Princeton (ASCOP) Model M telemeter ground station and Ampex Model 309C recorder unit. This recorded data could be played back repeatedly through the telemeter translator unit, where it was demodulated and appeared as a continuous voltage representing the recorded data. Control force and displacement were recorded directly with a Sanborn recorder as required.

Except for some modification to control force gradients, and the addition of a force measuring control wheel, the flight simulator was identical to that used by Hall in an investigation of human response. Details of the system may be found in Princeton Report No. 389 to be published.

Aircraft Dynamics and Control Forces

The lateral aircraft dynamics used were basically those of the "Navion" airplane except that aileron effectiveness was increased. This is the configuration which had been used with a previous investigation and was retained simply because it gave adequate performance within the limitations of the simulator servos. In retrospect, no valid reason can be stated for retaining the side-slip equation, particularly in view of the pilot having neither a means of sensing side-slip nor the rudder to cope with it. For the configuration used, no significant lateral oscillations were noted by the pilot. Maximum steady state roll rate was 30 degrees per second. The lateral configuration used was:

$$\begin{aligned}
\dot{\beta} + 0.5\beta + \dot{\psi} - 0.173\psi &= 0 \\
\ddot{\phi} + 6.7\dot{\phi} + 22.2\beta - 1.49\dot{\psi} &= 4\delta_a \\
0.072\dot{\phi} + 6.7\beta - \ddot{\psi} - 0.295\dot{\psi} &= 0
\end{aligned}$$

Lateral control force was maintained at a value of 2.1 inch-pounds per degree for the entire investigation. Lateral friction remained constant at a negligible value.

For the longitudinal dynamics, the short period approximation was used to simplify the computer problem and to facilitate the changing of stability configurations. The use of this approximation may be defended on the basis that the frequent control movements required in the tracking task would have masked any reasonable phugoid. The longitudinal dynamics used were of the form:

$$\frac{\dot{\theta}}{\Delta} = \frac{5(1 + 0.6\,s)}{1 + \frac{2\zeta}{\omega_n}s + \frac{s^2}{\omega_n^2}}$$

In a previous investigation in which the pilot was a test subject, a wide range of stability configurations involving changes in both short period frequency, ω_{sp}, and damping, ζ_{sp}, were flown. Tracking performance results were not available, but examination of the pilot's opinions indicated that the following configurations would be appropriate for this investigation:

$\omega_{sp} = 0.8$ $\zeta_{sp} = 0.4$	less than acceptable with "touchy" response
$\omega_{sp} = 0.4$ $\zeta_{sp} = 0.4$	quite acceptable but not optimum
$\omega_{sp} = 0.2$ $\zeta_{sp} = 0.4$	poor with sluggish response

These configurations cover a wide range of longitudinal dynamics and offer room for both improvement and depreciation with increasing control friction. Analog computer settings for these configurations were calculated and then adjusted to give precisely the desired characteristics. The response of these configurations to an elevator step function is shown in Figure 5.

Three longitudinal control force gradients were examined with the emphasis on the middle gradient. These values and corresponding steady state stick-force per g for a 300 feet per second aircraft are:

32 pounds per inch - - - - 40 pounds per g

17 pounds per inch - - - - 21 pounds per g

10 pounds per inch - - - - 12 pounds per g

Since the pilot has no sensation of normal acceleration in the flight simulator, the criterion of stick-force per g is not very meaningful. The pilot often interpreted rapid movement of the aircraft in terms of high g forces but this did not appear to deter his application of these forces.

Changes in longitudinal friction were accomplished by varying the load on a leather-lined shoe in contact with an aluminum portion of the feel mechanism. No measurable viscous friction or stiction were noted in the system; the mass of the longitudinal control was 0.14 slugs making inertia forces significant only for very rapid control movements.

Conduct of Tests

The testing was accomplished in nine periods extending over seventeen days. Four or five configurations were "flown" during each period. It was felt essential to complete testing in as short a period as possible in order to maintain pilot proficiency uniformly and to keep a common basis for pilot opinion evaluation of the various configurations.

In proceeding through the test program, an attempt was made to avoid gross changes in the configuration characteristics from one test to the next. It is believed that an abrupt change in configuration tends to over-emphasize the good or poor features, thus, coloring the pilot's opinion; increased learning time would be required as well. Each control force gradient was investigated completely before proceeding to the next. Beginning with light longitudinal friction, the friction was increased while alternating the three short period characteristics until a definite deterioration of pilot opinion was indicated. The friction was then decreased

to examine points initially skipped. This procedure was repeated for the heavy and light control gradients, although less completely.

In testing each configuration, it was first set up on the computer and either observed or tried by the engineer. From Sanborn recorder traces of longitudinal control force and displacement, the control friction was observed as half the difference in force as the control was moved nose up and nose down through center, averaged over several cycles. The loading on the friction shoe was adjusted as required to obtain the desired friction level. Belatedly, it was learned that the friction in the rear support bearing of the control shaft changed somewhat with the normal load, Thus, control friction might vary as much as 0.4 pounds depending on the pilot's technique in holding the control. It was observed that, during a tracking run, the pilot exerted a nearly constant load on the control wheel; however, care had not been taken to assure that the control wheel was held in the same manner while the control was oscillated during the pre- and post-test observation of control friction. Therefore, the recorded value of friction may differ slightly from the actual value experienced by the pilot for a given configuration; recorded values are probably low if the error was present.

The pilot first flew the configuration for a three minute learning period performing the tracking task previously described. This was found to be sufficient inasmuch as the pilot had considerable time in the simulator, and, as indicated above, there was only slight change in the aircraft characteristics from one to the next. Two tracking runs were then recorded. Each run was preceded by recording approximately thirty seconds of zero signal with the controls centered and fixed, the noise signal off, the horizon level and centered, and the target pip centered in the cross-hairs of the sight. The noise signal and the simulator were then turned on, and three minutes of the pilot's efforts to track the target were recorded.

Immediately after flying a configuration, the pilot evaluated it, assigning an adjective grade of good, acceptable, poor, or unacceptable, as well as a brief notation of salient features. The grading basis and the opinion data are tabulated in Appendix A.

Reduction of Data

Inasmuch as tracking data was in electrical form, it was found very convenient to use the analog computer for data reduction. The pilot opinion data had indicated a definite trend with increasing control friction. It was not known what form of the tracking error might best show similar trends. Through the use of rectifying, a linearized approximation of a square, integrating, and summing circuits, the data was available simultaneously in the following forms: $|\varepsilon|$, $\int|\varepsilon|$, ε^2 , $\int\varepsilon^2$ $\varepsilon_x^2+\varepsilon_y^2$, and $\int\Sigma\varepsilon^2$. Although only longitudinal parameters were changed in these tests, it was felt that the radius error, $\sqrt{\varepsilon_x^2+\varepsilon_y^2}$, was of primary significance. Accordingly, $\int\varepsilon_x^2+\varepsilon_y^2$ was recorded for each run with $\int|\varepsilon_x|$, $\int|\varepsilon_y|$, $\int\varepsilon_x^2$, and $\int\varepsilon_y^2$ recorded as secondary data.

In addition, a distribution analyzer was avilable which consisted of five precision timers each with a "gating" circuit biased to some desired value. When a low frequency signal was impressed on these gates, each timer summed the time that the signal exceeded the set bias. The distribution of the signal could then be deduced from the difference of adjoining timers. Using this scheme, the distribution of the radius tracking error was found in terms of percentage of time the error was less than 13, 27, 40, and 53 mils. Due to inherent limitations of the system, 13 mils was the smallest practical measurement of tracking error.

Because of both the approximations involved and the relative complexity of the data reduction system, several sources of error were present which tend to limit the repeatability of the results. Possible sources of data

error and the effect on an average tracking error of 33 mils were:

a. drift or missetting of zero bias - maximum error is 2 per cent for a 4 per cent drift.

b. attenuation of error signal during playback - this appears to be the most serious source of data reduction error. Variations as high as 6 per cent in $|\mathcal{E}|$ were noted in repeated playback of the same data. The most probable cause was a poor electrical connection between the translator unit and the computer problem board.

c. approximation of error square - the linear approximation results in a maximum data reduction error of 6 per cent although this error tends to cancel itself in an integration or summation of square of tracking error.

d. variation of reference voltage in distribution analyzer - a 0.5 volt variation in the reference voltage could result in a 20 per cent data error in the time tracking error was less than 13 mils but with only 5 per cent at 27 mils and negligible error at larger radii. When the effect of this variation was noticed, a better regulated reference voltage supply was substituted to minimize this error.

In an effort to reduce scatter of reduced data due to the above causes, all data was reduced twice. Where comparison of the two showed questionable results, the data was reduced once more. By this means, data reduction errors were minimized. It must be noted that an average variation of 5 per cent in mean tracking error occurred between successive runs of the same configuration.

It was originally intended to integrate tracking error over the full three minutes of each run. However, examination of the tracking error data indicated that it was periodic with the target noise signal. For this reason, only 133 seconds of the error signal for each run was used in reduction of data. After completing testing of the first six configurations, it was noticed that the noise signal excitation voltage was low due to deterioration of the dry-cell batteries used. The tracking error data for these runs has been scaled up proportionally by the ratio of the amplitude of the noise signal during the test to the standard noise signal. With one exception, the scaled-up data compares well with later data.

All of the various forms of the reduced data show, more or less, the same trends. The data is presented here as:

a. integral radius error squared normalized with respect to integral of untracked error,

$$\zeta = \frac{\int_0^{266} (\varepsilon_x^2 + \varepsilon_y^2)\,dt}{\int_0^{266} (\varepsilon_x^2 + \varepsilon_y^2)_N\,dt}$$

b. root-mean-square tracking error,

$$\bar{\varepsilon} = \left[\frac{1}{266}\int_0^{266} (\varepsilon_x^2 + \varepsilon_y^2)\,dt\right]^{1/2}$$

c. distribution of radius error - normalized time tracking error was less than 13, 27, 40, and 53 mils.

d. average radius error based on normalized error distribution - assumes that centroid of each increment of tracking error is at the mid-point of the increment.

e. average tracking error normalized by average untracked error,

$$Z = \frac{\varepsilon_{avg}}{(\varepsilon_{avg})_N}$$

RESULTS AND DISCUSSION

The results of this discussion fall into two distinct categories, quantitative pilot tracking proficiency and pilot opinion. The recording and reduction of tracking proficiency data was subject to some errors, which have been minimized by repetition of data reduction. Any residual scatter in the reduced data from this cause is of less significance than the variation in pilot tracking proficiency between successive runs with the same configuration. This variation averaged about 5 per cent in mean tracking error. It did not show any consistent pattern; this would indicate that it is merely scatter in performance rather than the result of insufficient practice. The pilot opinion data, on the other hand, was not subject to recording and reduction errors but did suffer from human variation. The pilot attempted to assign consistent adjective grades based

on his own definitions, which are found in Appendix A. In spite of this effort, some scatter of pilot opinion grades of like configurations was observed.

The radius tracking error for each of the various configurations is presented in Tables I and II in several forms. All show similar trends and presented here are only the variation with control friction of normalized integral radius error squared, Figure 6, and distribution of tracking error, Figure 7, which may be interpreted as time on target. The latter data shows less scatter due to less emphasis of very large tracking errors. For the heaviest control force gradient investigated, these plots show, rather remarkably, no general change in pilot tracking proficiency with increasing friction. For the case of the 17 pounds per inch gradient, a decay in tracking proficiency for control friction values in excess of about 4 pounds is noted. The greatest drop is shown for the $\omega_{sp} = 0.2$ cycles per second configuration. This trend is indicated by only one data point for each configuration and should be substantiated by repeated testing. The few configurations tested at the 10 pounds per inch gradient also show no variation of tracking proficiency up to 2.6 pounds control friction. No trend of increased tracking proficiency at very light friction levels is indicated for any configuration.

An anomaly in the tracking data is shown in Figure 6. Tracking proficiency with the $\omega_{sp} = 0.4$ cycles per second configuration for both the light and heavy control force gradients is comparable with the proficiency shown with the $\omega_{sp} = 0.8$ configuration. For the middle gradient, on the other hand, the pilot has tracked much more poorly with the $\omega_{sp} =$ 0.4 configuration without a similar deterioration of proficiency in the other two configurations. Data for the middle gradient was collected prior to taking data for the other two gradients; however, if some factor

were present at this time which depreciated pilot tracking proficiency of one configuration, it would seem reasonable to expect it to depreciate the performance in the others as well. The significance of this phenomenon is not understood. Time limitations prevented further investigation to verify this anomaly and to seek some explanation of its existence.

In Figure 8, the tracking error squared data has been cross-plotted to show the variation of tracking proficiency with control force gradient. The points are rather scattered, and for the range of control gradients investigated, no significant trend is shown. In the same figure, the time on target data has also been cross-plotted and shows a trend of improved tracking proficiency with the lighter control force gradient. In Figure 9, both the tracking error squared and the time on target data are cross-plotted to variation with short period frequency indicate improved tracking with higher frequencies. If the anomaly discussed above is disregarded tracking proficiency with the $\omega_{sp} = 0.4$ and $\omega_{sp} = 0.8$ configurations is seen to differ only slightly; it may be expected that tracking proficiency at higher frequencies would be reduced due to pilot response matching the aircraft oscillations. The distribution of the pilot tracking error for two typical configurations and the distribution of the target noise signal is presented in Figure 10.

The pilot opinion adjective grades for the configurations investigated are tabulated in Table I, and the amplifying remarks are recorded in Appendix A. Figure 11 is a plot of these opinions for the three control force gradients examined. Although the plot of pilot opinion shows considerable scatter, representative mean lines can be faired through the points for each stability characteristic. These mean lines consider both the adjective grades and the pilot remarks. For the 17 pound per inch gradient, Figure 11 (a), it is seen that the pilot opinion data for $\omega_{sp} =$ 0.2 and $\omega_{sp} = 0.4$ cycles per second depreciates uniformly with increasing

control friction. For the $\omega_{sp} = 0.8$ configuration, the presence of some friction is indicated as desirable. In both the $\omega_{sp} = 0.4$ and the $\omega_{sp} = 0.8$ configurations with very light friction the pilot's remarks invariably included mention of undesired longitudinal control inputs due to inattention, distraction or similar causes and of reduction of these inputs with slightly increased friction. This effect was more noticeable with the $\omega_{sp} = 0.8$ configuration, which had a more rapid response. Except for the very low short period frequencies, the pilot opinion data would indicate an optimum control friction of about one pound. For the 32 pounds per inch gradient, the same trend of deterioration of pilot opinion with increasing control friction is noted except that with the higher gradient, larger values of friction are tolerated by the pilot. For the light control gradient, the plot is too meager to show any trend.

Figure 12 shows a very interesting result which is obtained by cross-plotting the variation of pilot opinion with short period frequency and control friction. It is seen that there exists an optimum short period frequency for any friction level; the preference of a higher control force gradient and the toleration of larger control friction values with the larger gradient is also indicated. Similar information is presented in Figure 13, which is a cross-plot of the variation of pilot opinion with control force gradient for several values of control friction.

Referring once more to the pilot tracking proficiency data, it has been shown that the tracking proficiency is generally invarient with increasing control friction even though the pilot opinion deteriorates. The pilot is apparently able to adjust his response to compensate for the less desirable configuration. Cooper, in Reference 1, has noted a similar result in an investigation involving changes in stick force per g and control effectiveness. However, there must be a limit beyond which the pilot becomes so frustrated and fatigued by this friction that he is no longer able to adjust, and his tracking proficiency decays. The two

cases in the 17 pounds per inch control force gradient in which this tendency was noted correspond to the poorest pilot opinion grades recorded. On the basis of this comparison, it is hypothesized that the deterioration in pilot tracking proficiency occurs when the pilot opinion has fallen to unsatisfactory.

The pilot opinion remarks indicate that tracking with the less desirable configurations tested involves more effort and more concentration even though the tracking proficiency attained is nearly identical with that of better configurations. It is probable that a longer task or one requiring duties shared between tracking and some other function might result in a variation in tracking proficiency more nearly matching the variation in pilot opinion. If effort is to be the criterion, however, then the pilot should concede to the tracking data indication that the lighter control force gradient is the more suitable. Here, pilot opinion was weighted toward the more solid feeling of the heavy control gradient. In any case, it is the pilot opinion which will determine the degree of acceptance of an aircraft configuration, and the designer should place primary emphasis on valid pilot opinion data when available. This investigation indicates that the pilot tracking proficiency will take care of itself.

CONCLUSIONS

Any conclusions derived from the results of this investigation must be tempered by the fact that they are based on the opinions and tracking proficiency of only one pilot, who, although representative of a large group of experienced aviators, is still an individual. Pilots in general are noted for their individualist characteristics. Further, this data has been obtained from a flight simulator for a limited number of runs using a specific task. Certain tendencies have been indicated which may

have general application but should be subject to further verification.

The results of this investigation show no significant change in pilot tracking proficiency with variation of control friction from near zero to moderate values. There is an indication of decay of tracking proficiency near the friction value where the pilot opinion becomes unsatisfactory. With larger control force gradients, pilot tracking proficiency is maintained with larger values of control friction than were accommodated at lesser gradients.

Pilot opinion data indicates that larger control force gradients are desirable; conversely, the tracking data shows improved tracking with the lighter control gradients.

Both pilot opinion and pilot tracking proficiency indicate an optimum short period frequency in the range 0.4 to 0.8 cycles per second with short period damping of 0.4.

The pilot opinion data indicates that some control friction is desirable to mask unintended control inputs. This is particularly true of the higher short period frequencies. The pilot opinion of a particular configuration otherwise deteriorates uniformly with increasing control friction.

It is concluded that pilot opinion data should receive primary emphasis in judging the best characteristics for an aircraft control system.

REFERENCE

1. Cooper, George E.; "Understanding and Interpreting Pilot Opinion", Aero. Eng. Rev.; Vol. 16, No. 3, March 1957.

Table I (a)

Results of Test Runs
Mean Error

Stick Force Gradient 10 lb./in.
Short Period Damping Ratio 0.4

Short Period Frequency c.p.s.	Friction lb.	Pilot No.	Pilot Opinion	Z	ζ	Mean Error mils	RMS Error mils
0.80	1.3	1	P+	0.63	0.41	25	28
0.40	0.3	1	A	0.61	0.38	24	27
	1.3	1	A+	0.62	0.38	24	27
	2.6	1	A	0.62	0.38	24	27
0.20	1.3	1	U+	0.68	0.48	26	30
	1.4	2	A	0.80	0.67	31	36

Z Mean error, radius, normalized by the mean radius of the random noise tracked, dimensionless

ζ Mean square error, radius, normalized by the mean square radius of the noise

Table I (b)

Results of Test Runs
Mean Error

Stick Force Gradient 17 lb./in.
Short Period Damping Ratio 0.4

Short Period Frequency c.p.s.	Friction lb.	Pilot No.	Pilot Opinion	Z	ζ	Mean Error mils	RMS Error mils
0.80	0.2	1	A-	0.60	0.37	23	27
	0.4	1	P+	0.60	0.37	23	25
	1.2	1	P+	0.62	0.37	25	27
	1.3	1	A+	0.67	0.45	26	30
	1.4	2	A-	0.72	0.53	28	32
	2.5	1	A	0.58	0.35	23	26
	6.0	1	P-	0.69	0.46	27	29
0.40	0.3	1	G	0.70	0.49	27	31
	0.5	1	A	0.71	0.51	28	32
	0.8	1	A+	--	--	--	--
	1.0	1	A+	0.72	0.55	28	33
	1.3	1	A+	0.71	0.51	28	31
	2.5	1	A-	0.71	0.53	28	32
	5.4	1	P	0.71	0.55	28	33
0.20	0.2	1	P+	0.73	0.59	28	34
	1.2	1	P-	0.68	0.45	26	29
	2.8	1	U+	0.70	0.50	27	30
	5.3	1	U	0.85	0.73	33	37

Z Mean error, radius, normalized by the mean radius of the random noise tracked, dimensionless

ζ Mean square error, radius, normalized by the mean square radius of the noise

Table I (c)

Results of Test Runs
Mean Error

Stick Force Gradient 32 lb./in.
Short Period Damping Ratio 0.4

Short Period Frequency c.p.s.	Friction lb.	Pilot No.	Pilot Opinion	Z	ζ	Mean Error mils	RMS Error mils
0.80	0.8	1	A+	0.65	0.41	26	28
	2.6	1	G	0.61	0.37	24	27
	5.6	1	G-	0.63	0.39	25	27
0.40	0.4	1	A+ to G-	0.60	0.36	23	26
	0.9	1	G-	0.65	0.41	26	28
	1.2	2	G	0.74	0.50	29	31
	1.4	1	G-	0.59	0.36	23	26
	2.8	1	A+	0.68	0.45	27	30
	5.7	1	A+	0.66	0.39	26	28
	10.0	1	P	0.62	0.40	25	28
	10.0	2	P	0.72	0.52	33	32
0.20	1.0	1	P+	0.78	0.59	30	33
	2.7	1	P+	0.74	0.56	29	33

Z Mean error, radius, normalized by the mean radius of the random noise tracked, dimensionless

ζ Mean square error, radius, normalized by the mean square radius of the noise

Table II (a)

Results of Test Runs
Distribution of Error

Stick Force Gradient 10 lb./in.
Short Period Damping Ratio 0.4

Short Period Frequency	Friction	Pilot No.	Pilot Opinion	Normalized time during which error was below specified number of mils			
				13 mils	27 mils	40 mils	53 mils
c.p.s.	lb.						
0.80	1.3	1	P+	0.27	0.63	0.85	0.95
0.40	0.3	1	A	0.23	0.65	0.86	0.97
	1.3	1	A+	0.21	0.65	0.87	0.97
	2.6	1	A	0.16	0.66	0.87	0.96
0.20	1.3	1	U+	0.19	0.58	0.84	0.94
	1.4	2	A	0.11	0.44	0.73	0.87

Table II (b)

Results of Test Runs
Distribution of Error

Stick Force Gradient 17 lb./in.
Short Period Damping Ratio 0.4

Short Period Frequency c.p.s.	Friction lb.	Pilot No.	Pilot Opinion	Normalized time during which error was below specified number of mils			
				13 mils	27 mils	40 mils	53 mils
0.80	0.2	1	A-	0.27	0.64	0.86	0.98
	0.4	1	P+	0.26	0.68	0.87	0.96
	1.2	1	P+	0.20	0.63	0.86	0.97
	1.3	1	A+	0.21	0.58	0.83	0.94
	1.4	2	A-	0.17	0.55	0.80	0.91
	2.5	1	A	0.26	0.65	0.91	0.97
	6.0	1	P-	0.19	0.55	0.82	0.95
0.40	0.3	1	G	0.15	0.51	0.83	0.94
	0.5	1	A	0.16	0.56	0.80	0.92
	0.8	1	A+	--	--	--	--
	1.0	1	A+	0.18	0.55	0.78	0.91
	1.3	1	A+	0.17	0.56	0.80	0.93
	2.5	1	A-	0.19	0.53	0.79	0.92
	5.4	1	P	0.18	0.56	0.78	0.90
0.20	0.2	1	P+	0.16	0.51	0.79	0.93
	1.2	1	P-	0.16	0.56	0.84	0.97
	2.8	1	U+	0.19	0.55	0.83	0.92
	5.3	1	U	0.11	0.39	0.69	0.89

Table II (c)

Results of Test Runs
Distribution of Error

Stick Force Gradient 32 lb./in.
Short Period Damping Ratio 0.4

Short Period Frequency c.p.s.	Friction lb.	Pilot No.	Pilot Opinion	Normalized time during which error was below specified number of mils: 13 mils	27 mils	40 mils	53 mils
0.80	0.8	1	A+	0.18	0.61	0.86	0.94
	2.6	1	G	0.24	0.65	0.87	0.96
	5.6	1	G-	0.20	0.64	0.86	0.95
0.40	0.4	1	A+ to G-	0.26	0.65	0.88	0.98
	0.9	1	G-	0.17	0.62	0.84	0.95
	1.2	2	G	0.11	0.52	0.80	0.93
	1.4	1	G-	0.29	0.71	0.87	0.97
	2.8	1	A+	0.17	0.57	0.82	0.95
	5.7	1	A+	0.13	0.62	0.85	0.96
	10.0	1	P	0.23	0.64	0.86	0.96
	10.0	2	P	0.13	0.50	0.75	0.92
0.20	1.0	1	P+	0.15	0.47	0.77	0.93
	2.7	1	P+	0.19	0.50	0.78	0.90

FIG 1

SCHEMATIC OF FLIGHT SIMULATOR

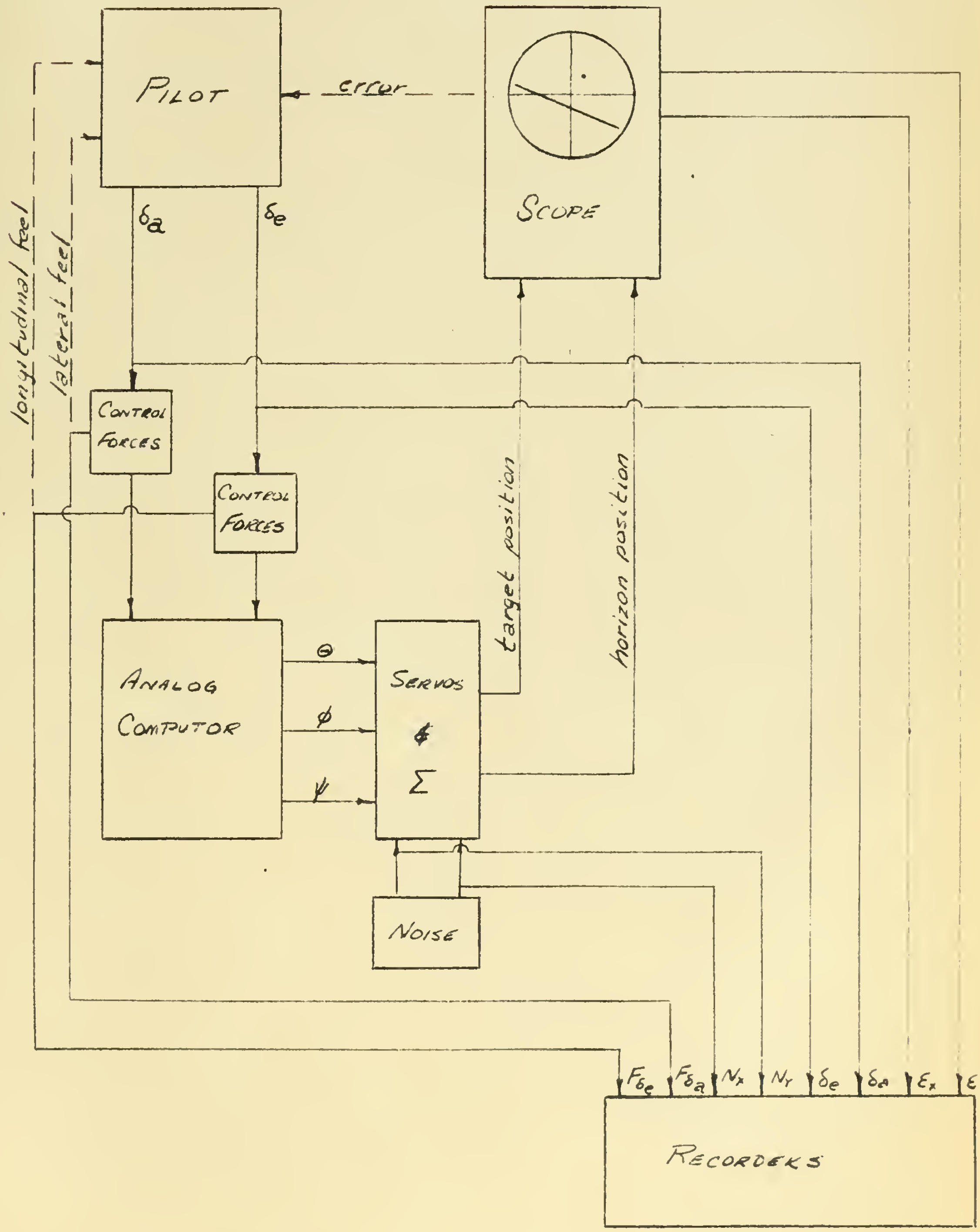


FIG. 2

PILOT'S PRESENTATION

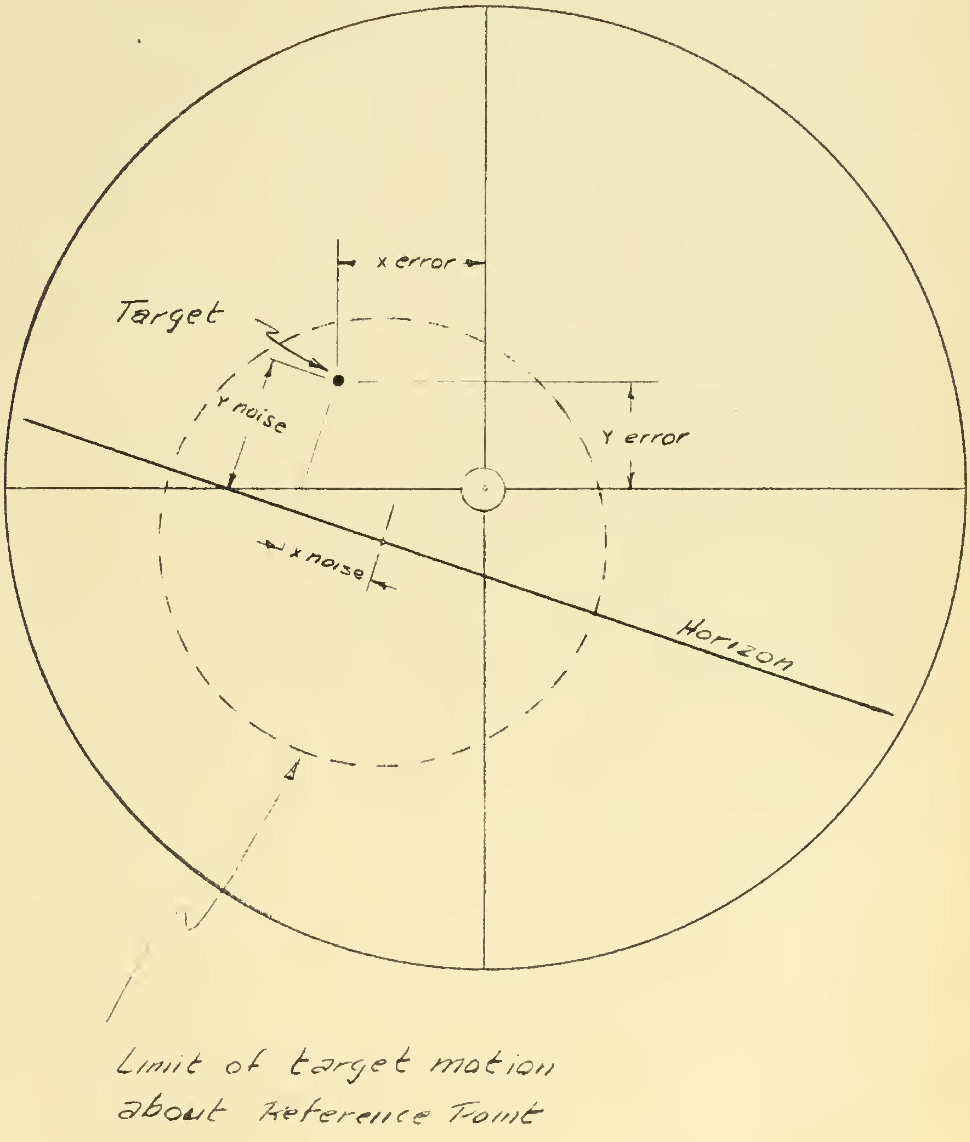
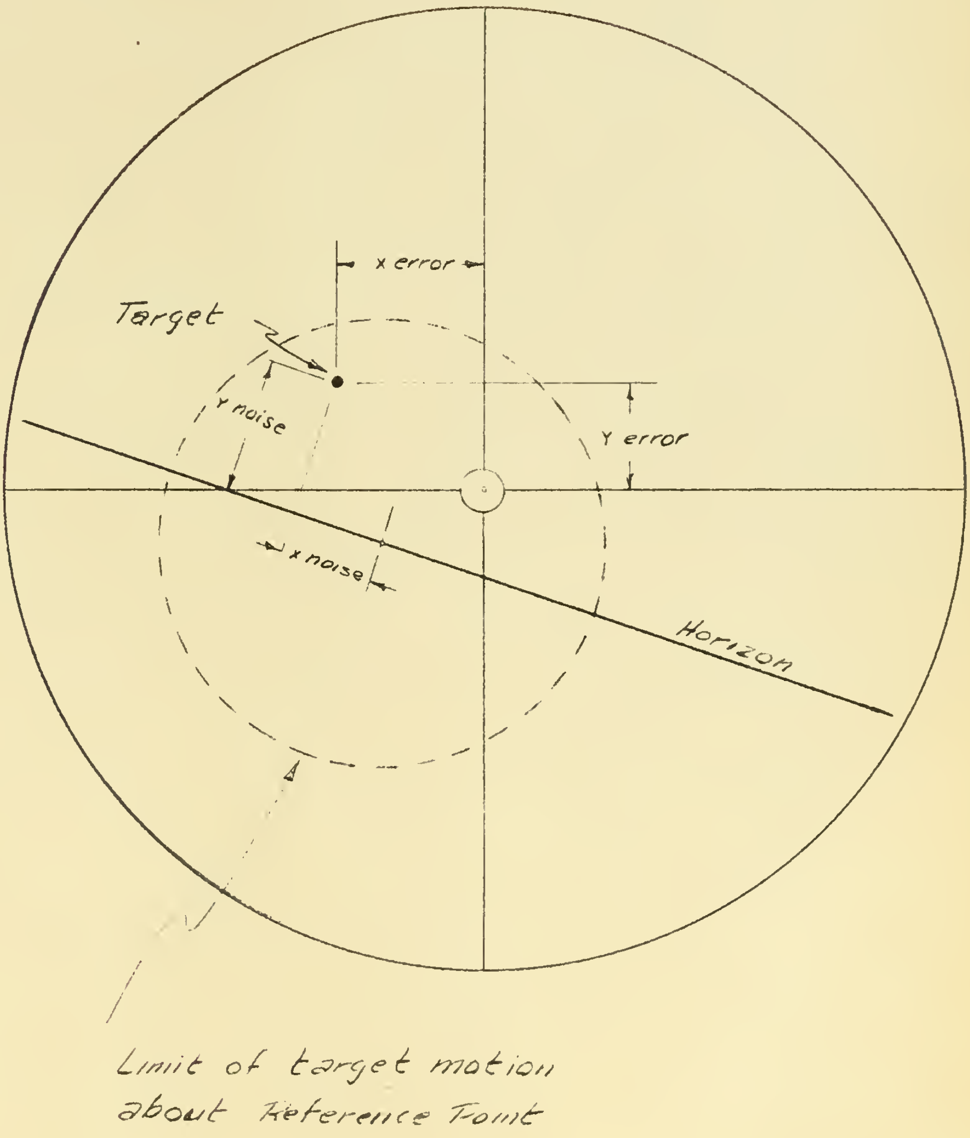


FIG. 2

PILOT'S PRESENTATION



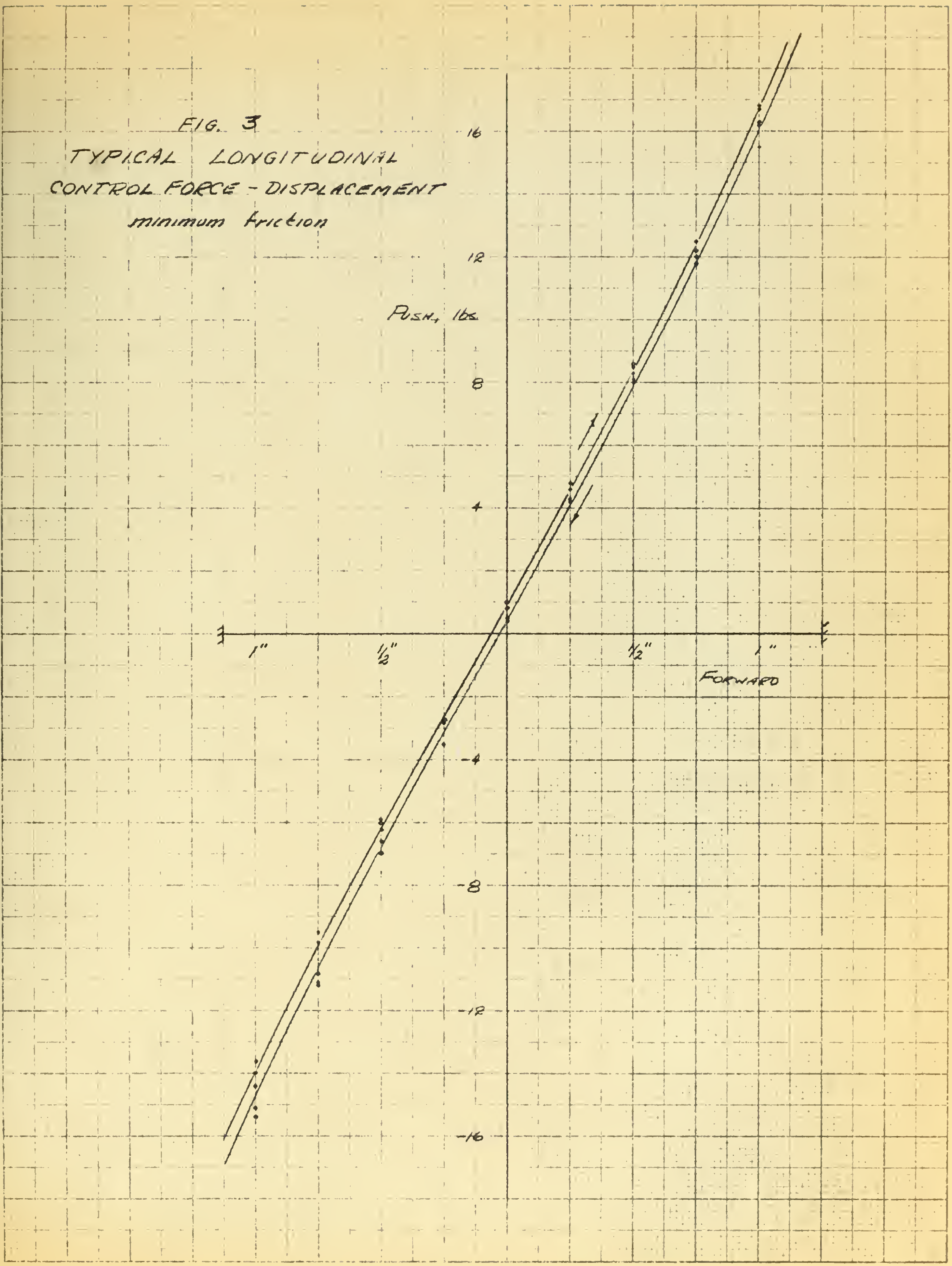


FIG. 3
TYPICAL LONGITUDINAL
CONTROL FORCE - DISPLACEMENT
minimum friction
PUSH, lbs.
16
12
8
4
-4
-8
-12
-16
1"
1/2"
1/2"
1"
FORWARD

FIG 4

LATERAL

CONTROL FORCE - DISPLACEMENT

5.25 in. arm

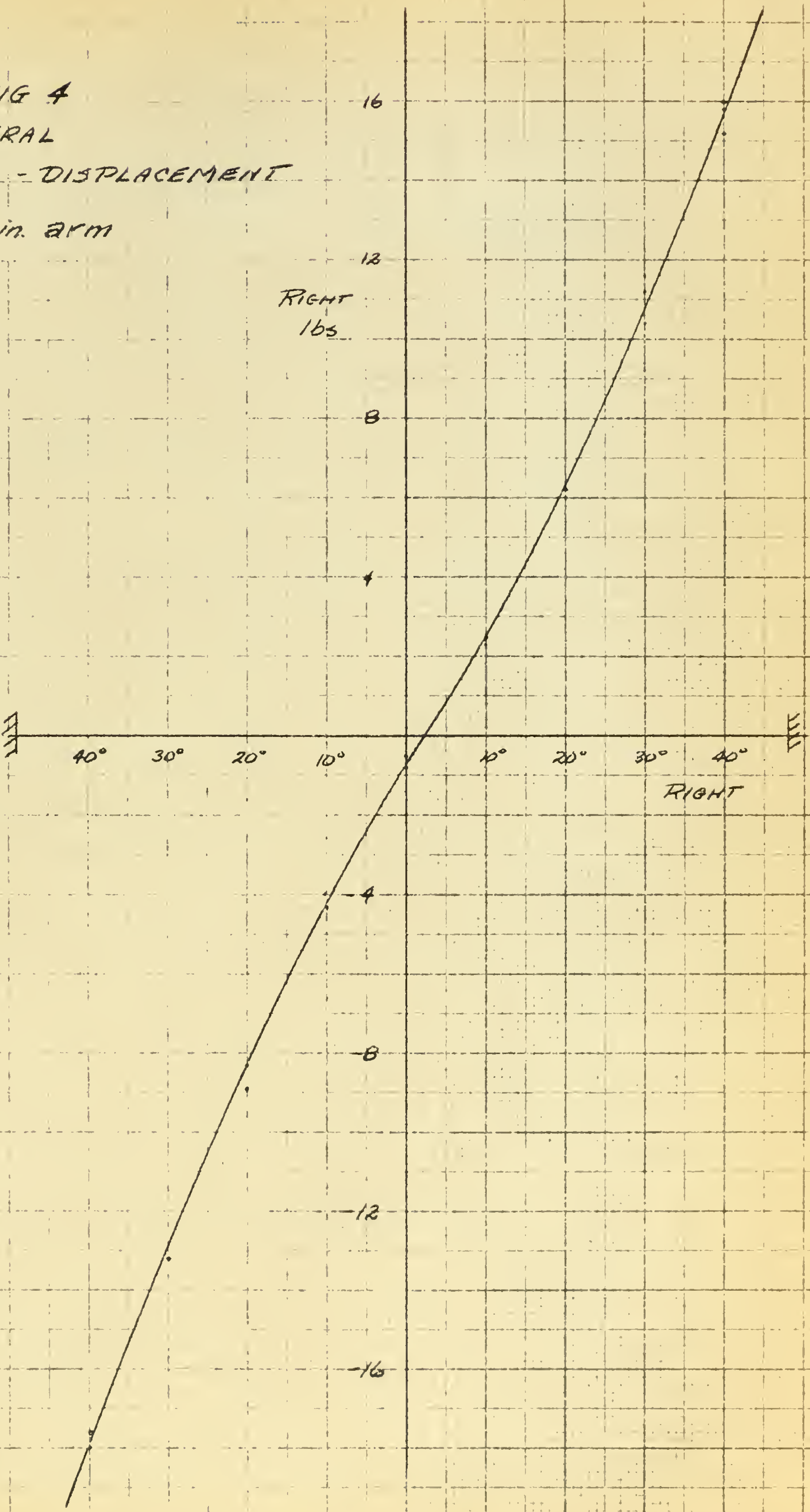
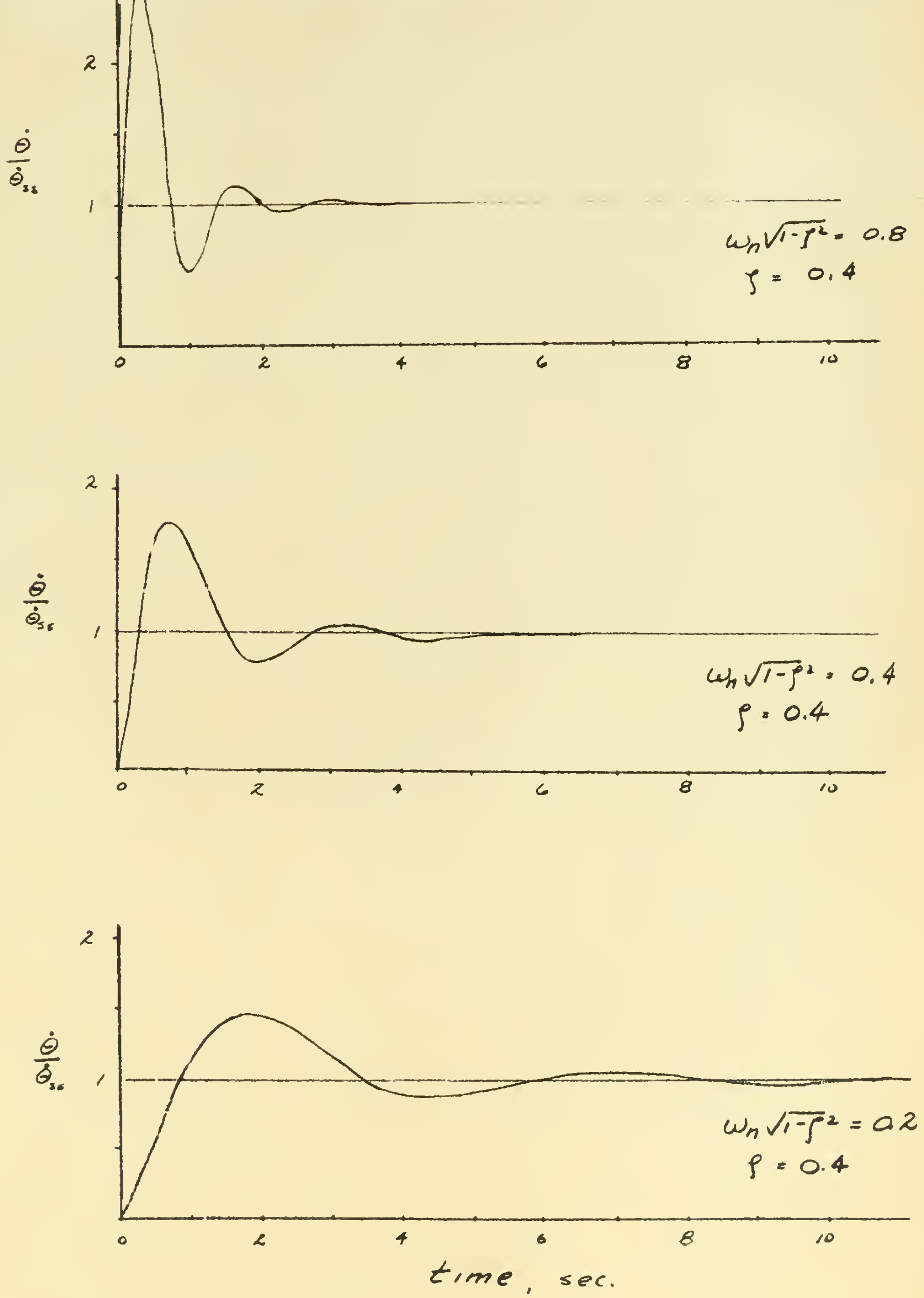


FIG 5

RESPONSE OF LONGITUDINAL CONFIGURATIONS TO ELEVATOR STEP FUNCTION

$$\frac{\dot{\Theta}}{\Delta} = \frac{5(1+0.6s)}{\left(1+\frac{2\zeta}{\omega_n}s+\frac{s^2}{\omega_n^2}\right)}$$



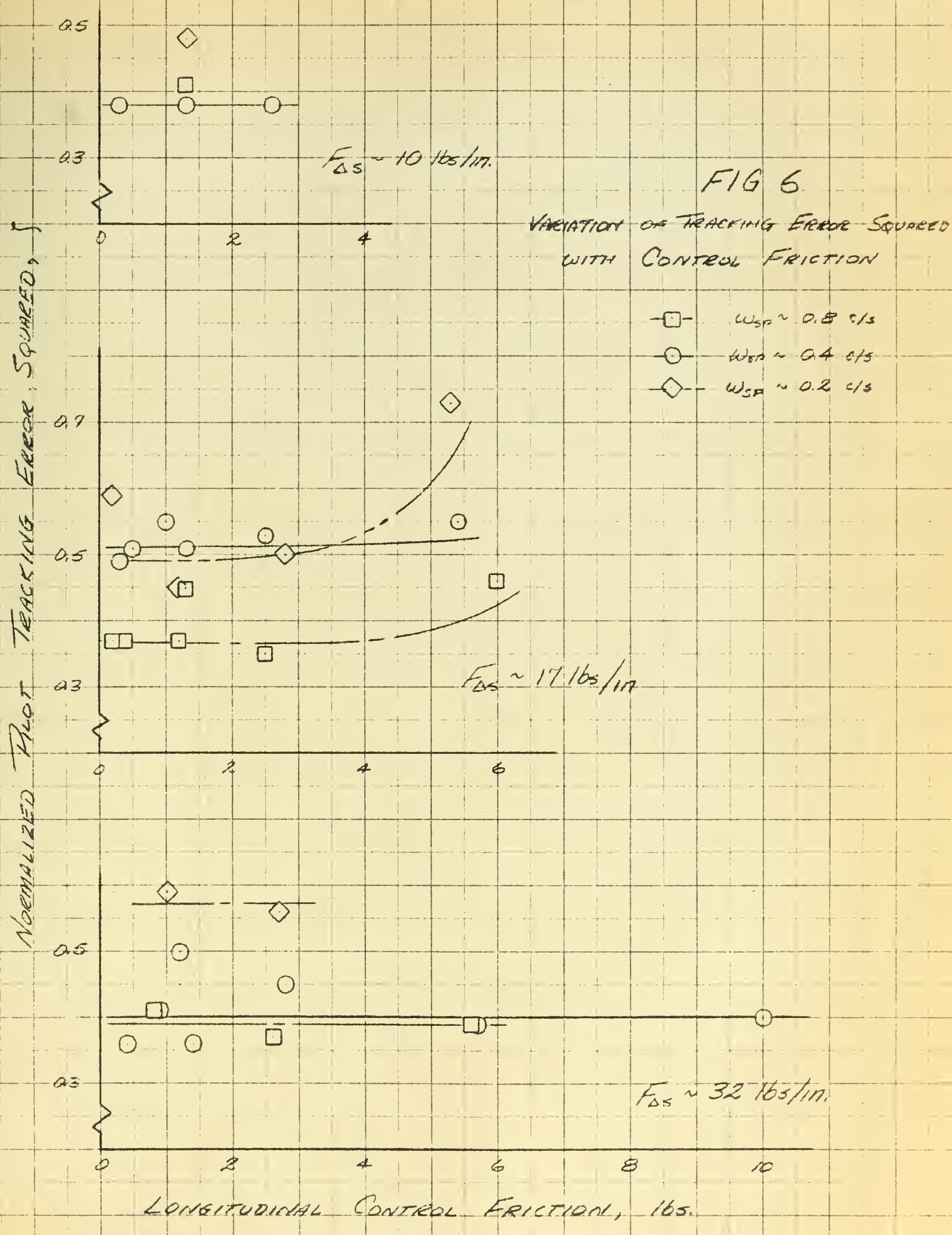


FIG 6

Variation of Tracking Error Squared with Control Friction

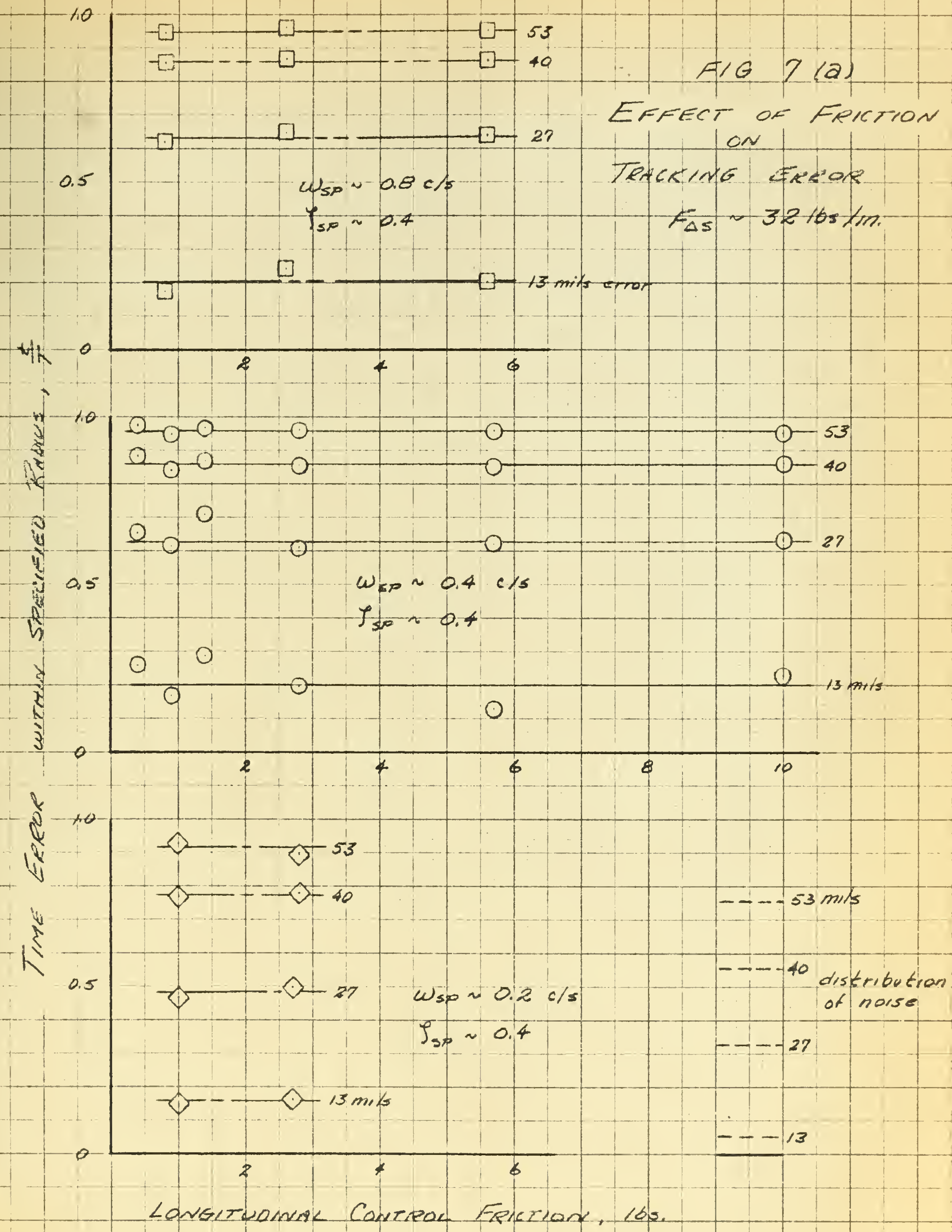


FIG 7 (a)
EFFECT OF FRICTION ON TRACKING ERROR
$F_{\Delta s} \sim 32$ lbs/in.

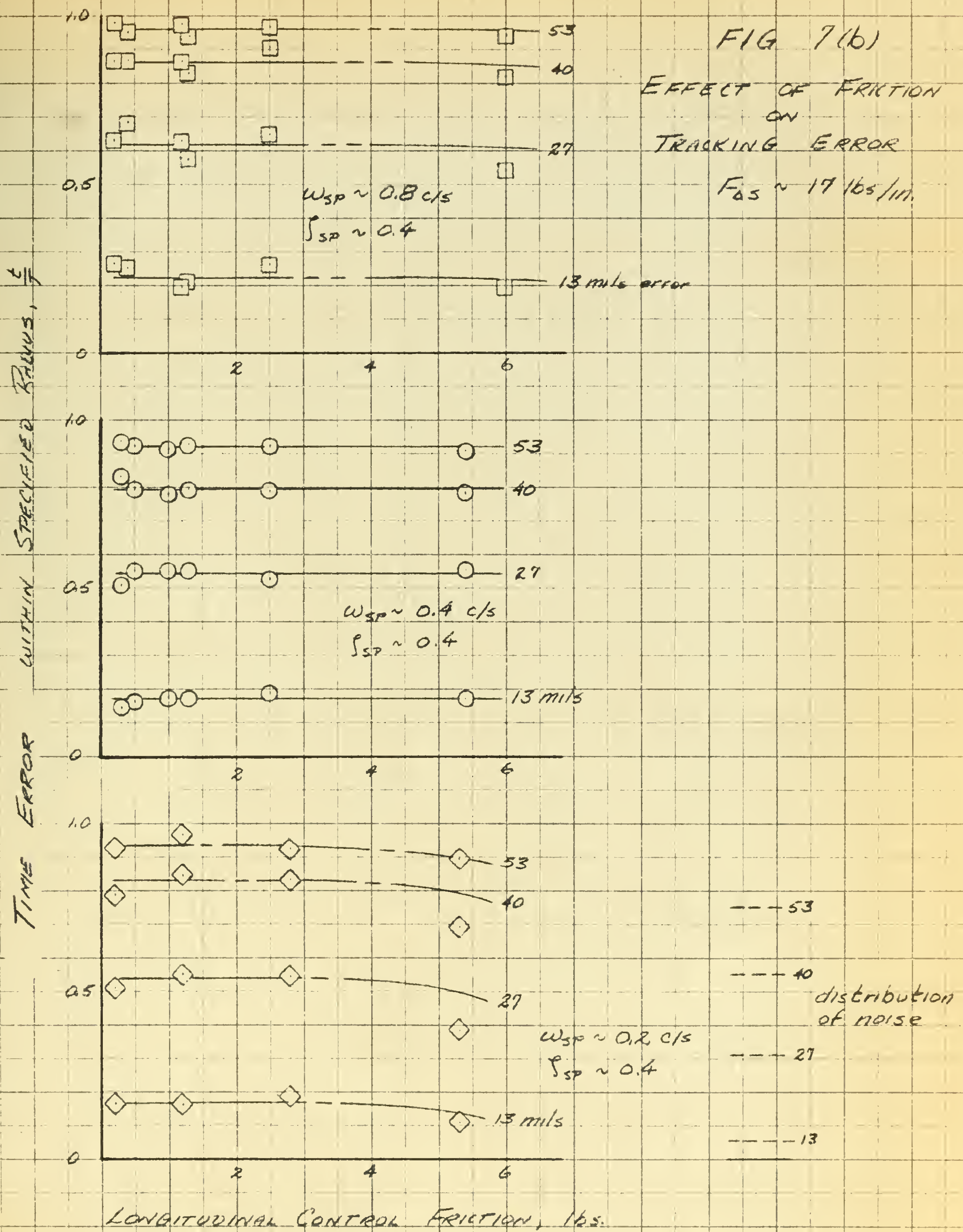


FIG 7(b)
EFFECT OF FRICTION ON TRACKING ERROR
$F_{AS} \sim 17$ lbs/in.
TIME ERROR WITHIN SPECIFIED RADIUS, $\frac{t}{T}$
1.0
0.5
0
2
4
6
53
40
27
13 mils error
$\omega_{SP} \sim 0.8$ c/s
$\zeta_{SP} \sim 0.4$
13 mils
$\omega_{SP} \sim 0.4$ c/s
$\zeta_{SP} \sim 0.4$
$\omega_{SP} \sim 0.2$ c/s
$\zeta_{SP} \sim 0.4$
53
40
27
13
distribution of noise
LONGITUDINAL CONTROL FRICTION, lbs.

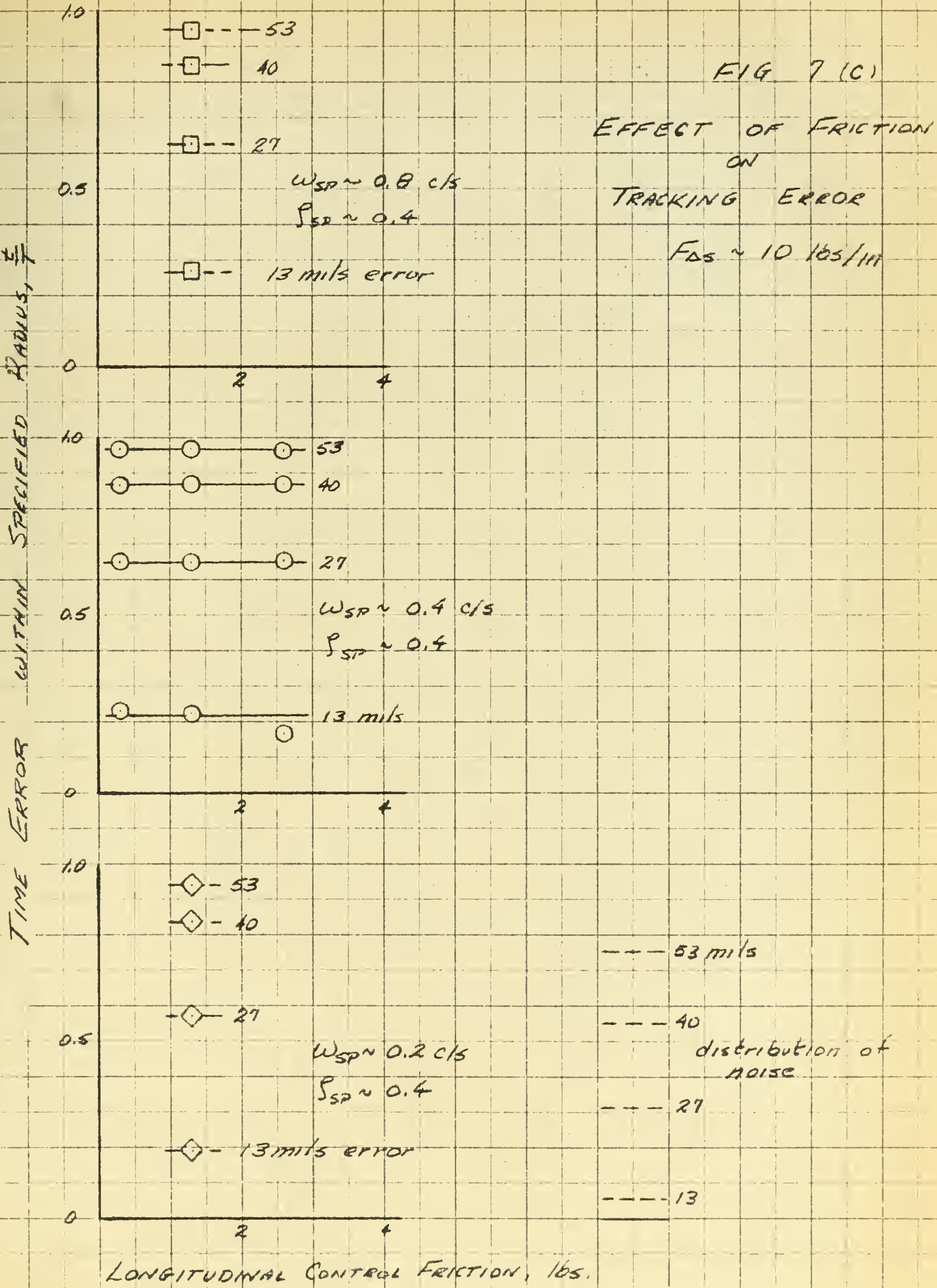


FIG 7 (C)

EFFECT OF FRICTION ON TRACKING ERROR

FIG 8

VARIATION OF TRACKING PROFICIENCY
WITH
CONTROL FORCE GRADIENT

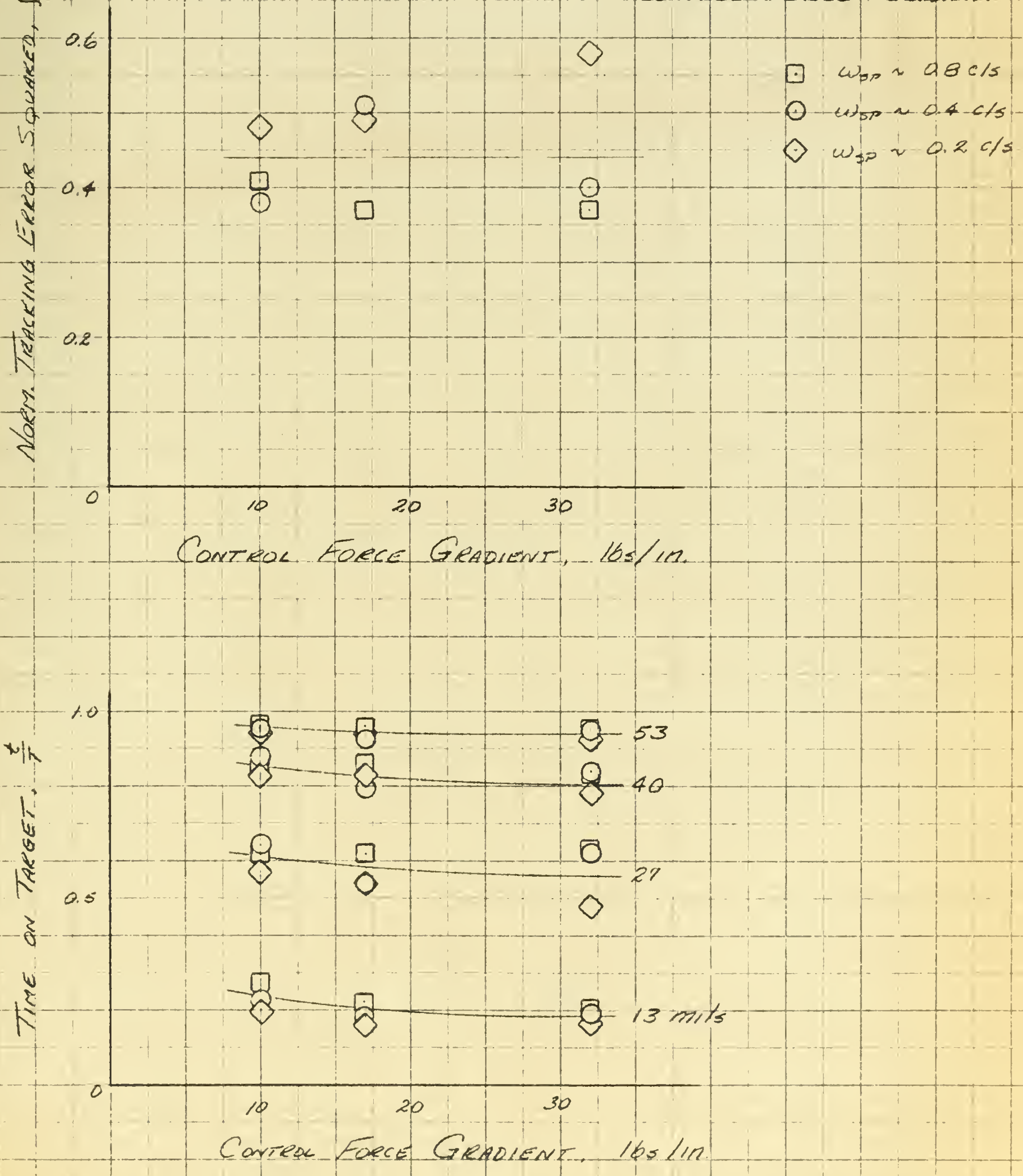


FIG 9

VARIATION OF TRACKING PROFICIENCY WITH SHORT PERIOD FREQUENCY

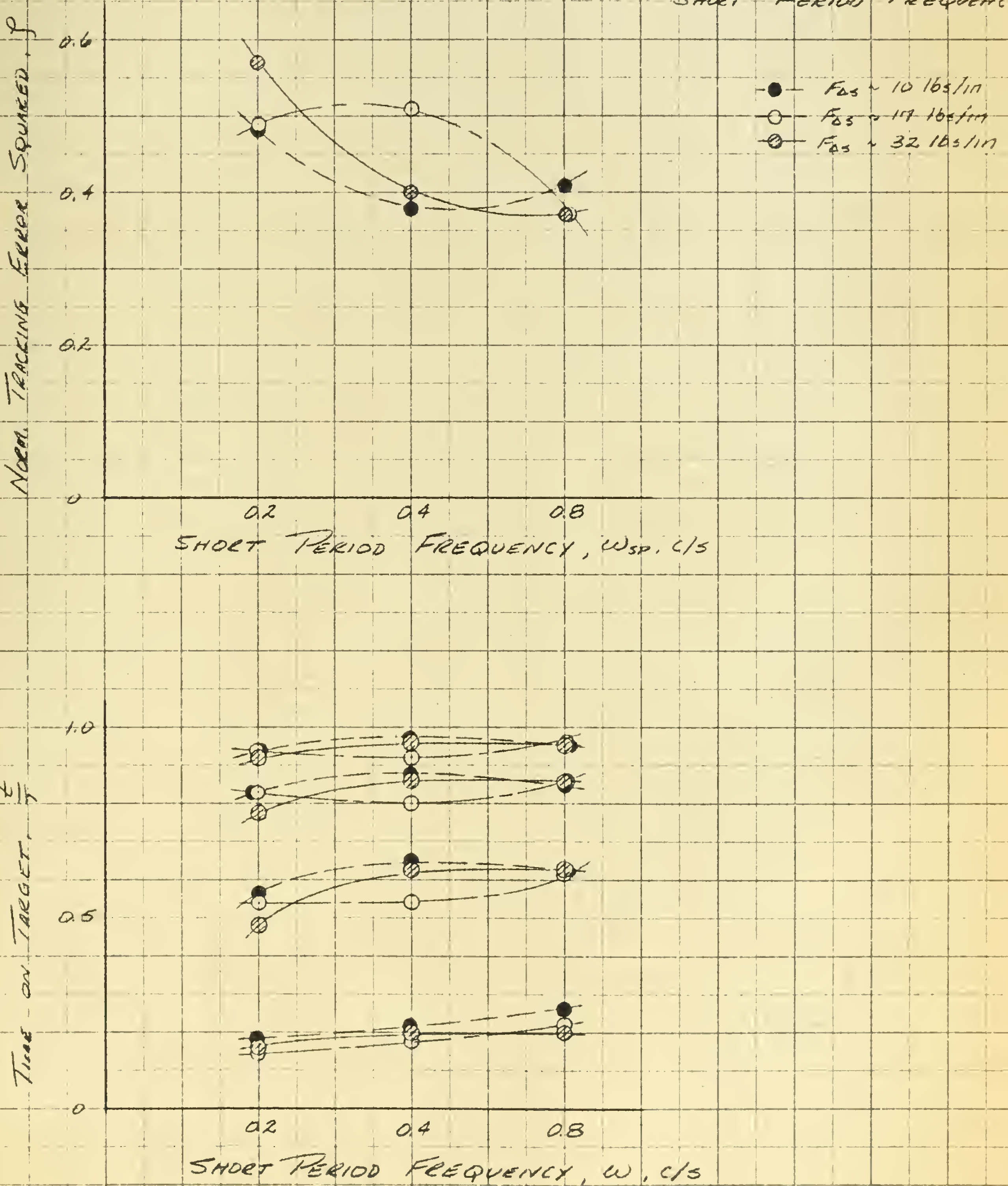


FIG 10

TYPICAL TRACKING ERROR DISTRIBUTIONS

F_{DS} = 17 lbs/in

ω_{SP} = 0.8 c/s

ζ_{SP} = 0.4

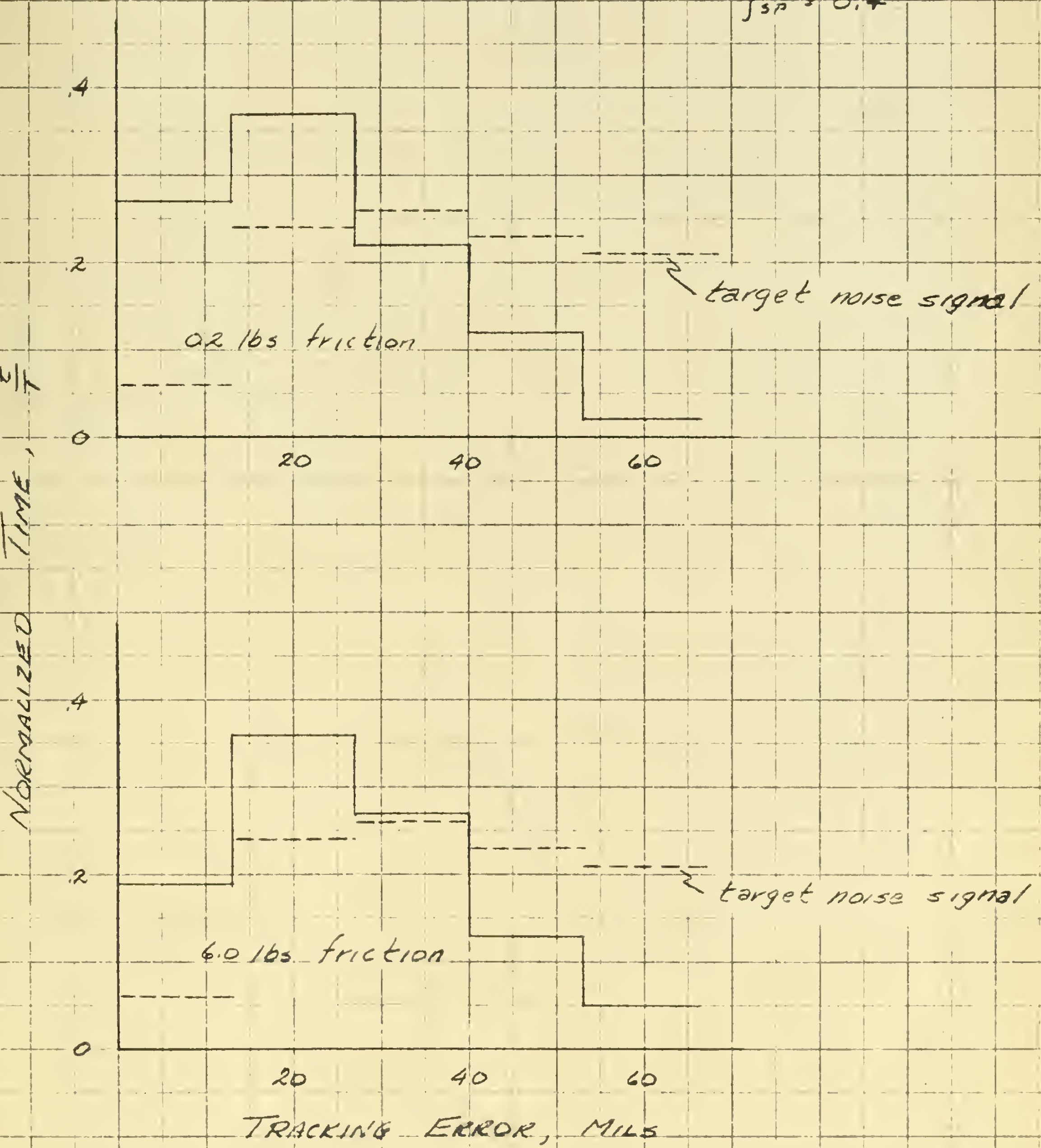
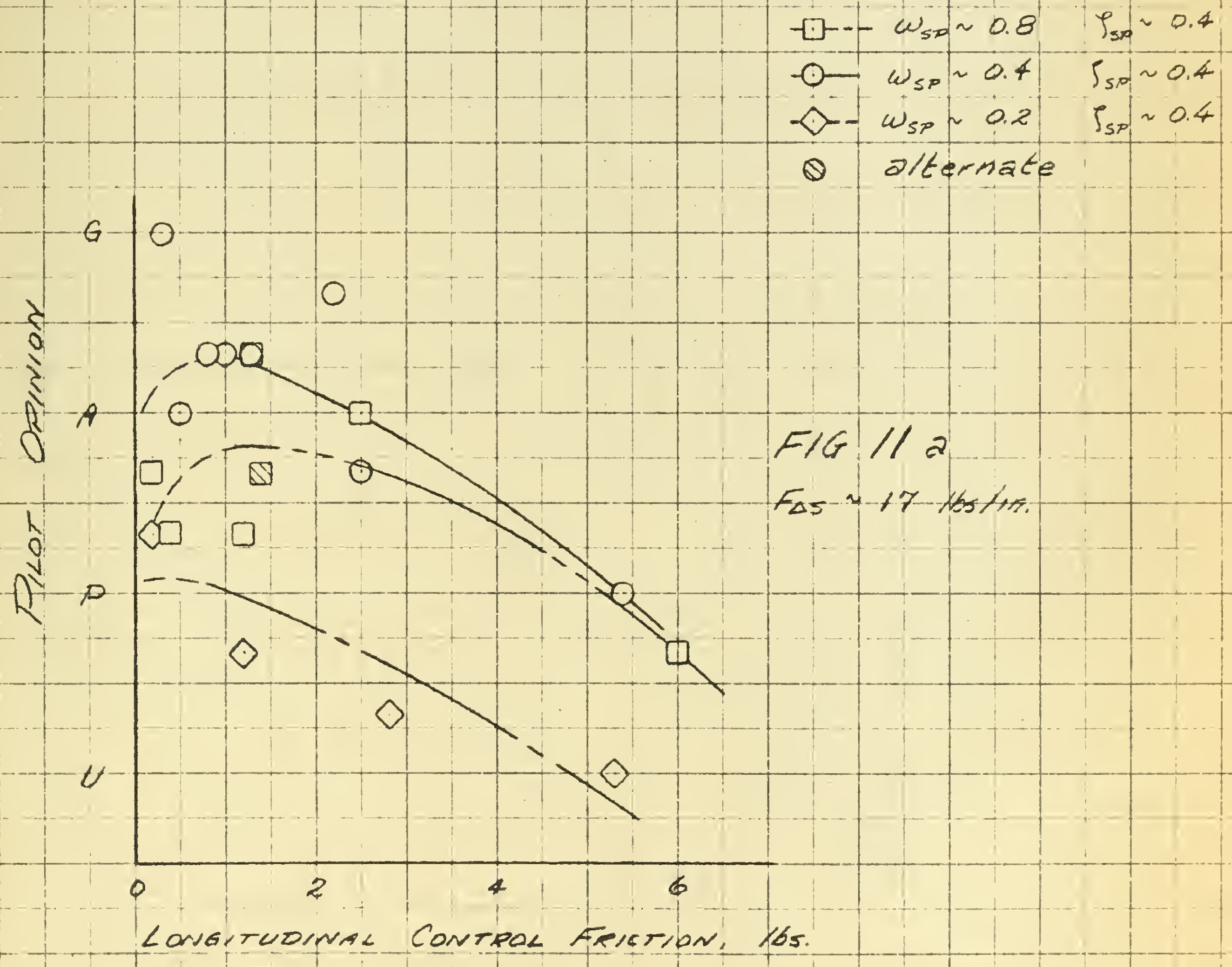


FIG 11

VARIATION OF PILOT OPINION WITH LONGITUDINAL CONTROL FRICTION



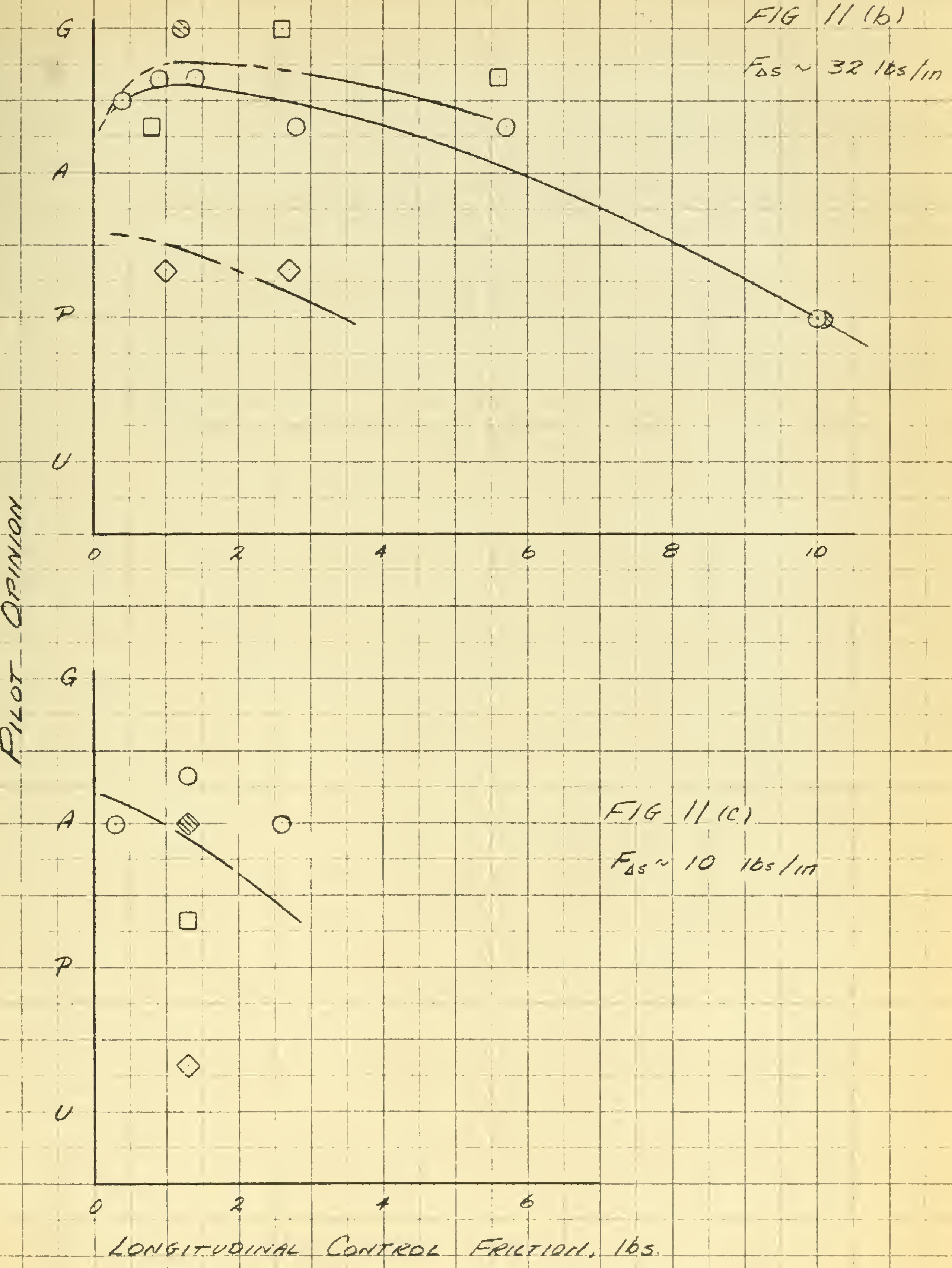


FIG 11 (b)
$F_{\Delta s}$ ~ 32 lbs/in
G
A
P
U
0
2
4
6
8
10
PILOT OPINION
G
A
P
U
FIG 11 (c)
$F_{\Delta s}$ ~ 10 lbs/in
0
2
4
6
LONGITUDINAL CONTROL FRICTION, lbs.

FIG 12

VARIATION OF PILOT OPINION WITH SHORT PERIOD FREQUENCY AND CONTROL FRICTION

$\zeta_{SP} \sim 0.4$

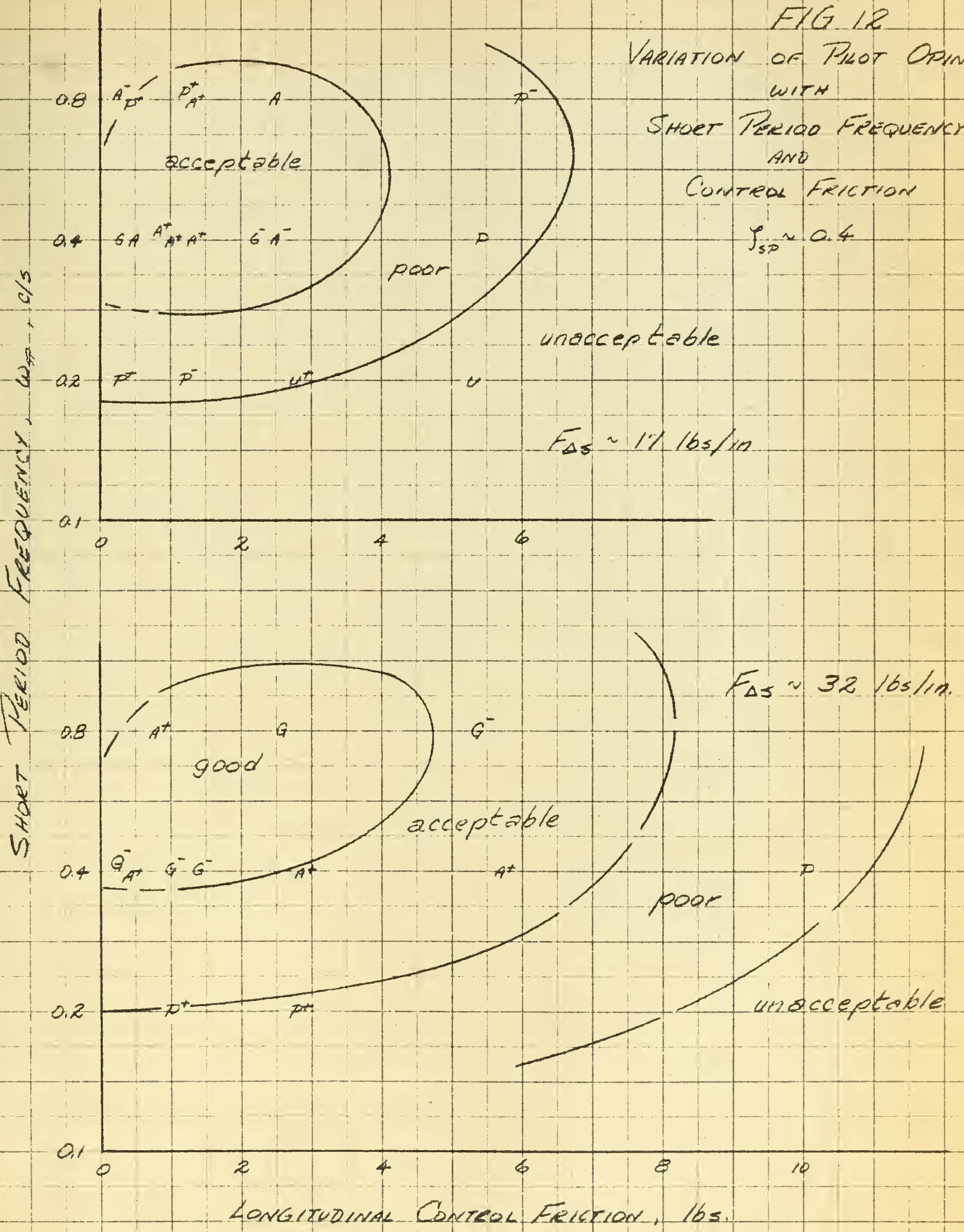
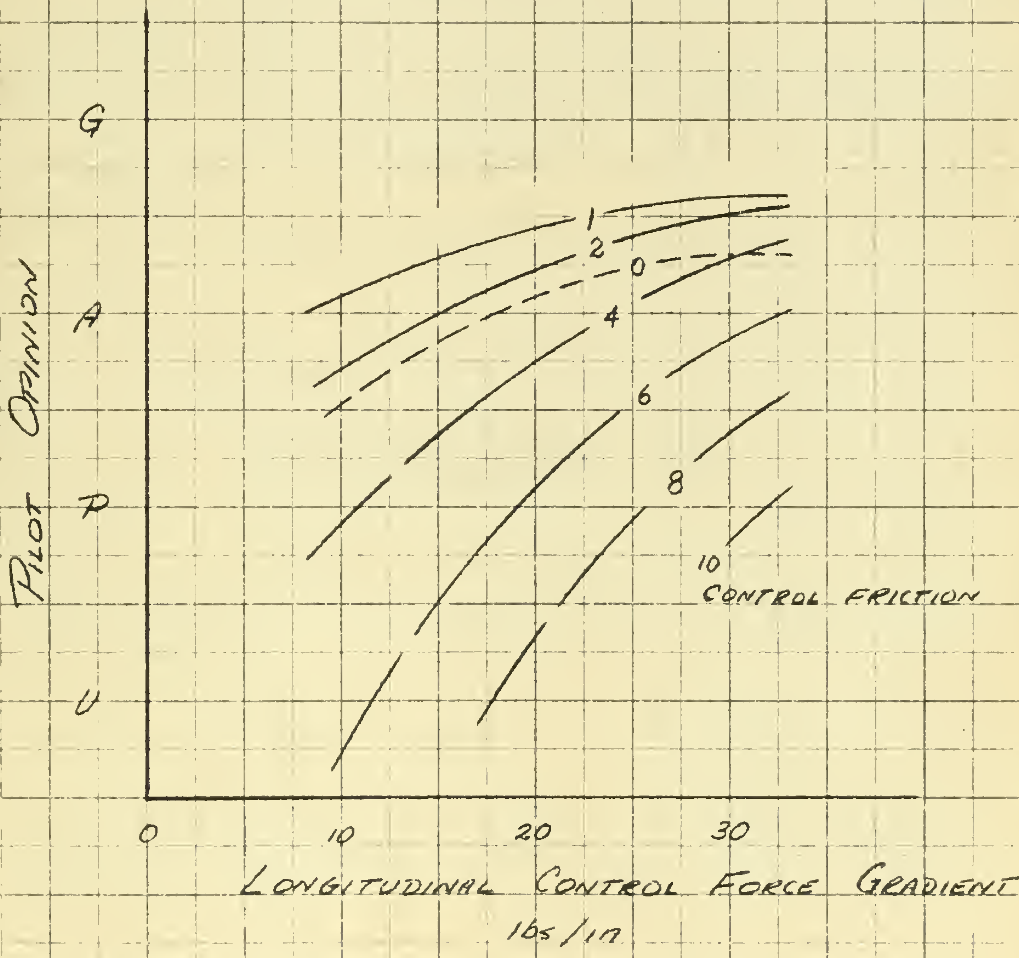


FIG 13

VARIATION OF PILOT OPINION
WITH
LONG. CONTROL FORCE GRADIENT

$\omega_{sp} \sim 0.4$
$\zeta_{sp} \sim 0.4$



APPENDIX A

PILOT COMMENTS ON INDIVIDUAL CONFIGURATIONS

Definitions of Adjective Grades Employed in Pilot Opinions

The following definitions were made by pilot #1 prior to the commencement of testing. Pilot #2 concurred with these definitions.

GOOD	No objectionable characteristics of significant magnitude observed.
ACCEPTABLE	Satisfactory, but not good.
POOR	Possessed of characteristics which render tracking (or flying) difficult to the point of being seriously objectionable.
UNACCEPTABLE	Impossible or extremely difficult to use for tracking and/or dangerous to fly.

Control Force Gradient - 32 pounds per inch

Short Period Frequency - 0.8 c/s
Short Period Damping - 0.4

Friction - 0.8 pounds — Pilot No. 1

Acceptable Plus: My only objection was to a slight overshoot. Friction seemed very light.

Friction - 2.6 pounds — Pilot No. 1

Good Minus: Configuration (aircraft) had a tendency to overshoot and response was fairly rapid. It would have yielded responses of significant magnitude to inadvertent control motions except the friction helped suppress such motions.

Friction - 5.6 pounds — Pilot No. 1

Good Minus: Some overshoot, but friction helped me avoid rapid movements which would cause really objectionable overshoot.

Short Period Frequency - 0.4 c/s
Short Period Damping - 0.4

Friction - 0.4 pounds — Pilot No. 1

Acceptable Plus to Good Minus: Halfway, acceptable to good. Friction very light, inadvertent stick motions were experienced, but the aircraft did not react at all violently to these motions.

Friction - 0.9 pounds Pilot No. 1

Good Minus: I liked the feel of the controls and the longitudinal dynamics. Not considered an unqualified good because it was not damped as heavily as I would like.

Friction - 1.2 pounds Pilot No. 2

Good: No other comment.

Friction - 1.4 pounds Pilot No. 1

Good Minus: Not an unqualified good only because of some overshoot. Friction (light) seemed helpful in making positive control movements.

Friction - 2.8 pounds Pilot No. 1

Acceptable Plus: Control friction helped me hold the stick in desired positions.

Friction - 5.7 pounds Pilot No. 1

Acceptable Plus: Not quite in the "good" bracket. Breakout force caused some undesired longitudinal oscillations. Friction seemed to help me hold small elevator deflections, but it wasn't heavy enough to be dependable at usual elevator deflections. Net effect of friction - somewhat detrimental.

Friction - 10.0 pounds Pilot No. 1

Poor: Friction seemed very heavy. Longitudinal control movements had to be slow and deliberate or a greater movement of controls than desired would follow overcoming breakout force.

Friction - 10.0 pounds Pilot No. 2

Poor: Work involved most annoying but tracking not too bad. Smooth control impossible.

Short Period Frequency - 0.2 c/s
Short Period Damping - 0.4

Friction - 1.0 pounds Pilot No. 1

Poor Plus: Low frequency of short period. With this friction (light) and

stick force (heavy) it was manageable, however, the higher stick force tended to prevent large displacements which are detrimental with the low frequency.

Friction - 2.7 pounds Pilot No. 1

Poor Plus: Short period slow. I tried to track it by applying elevator pulses and using resulting pitch rates. Friction noticeable; no help, but it didn't seem to bother me.

Control Force Gradient - 17 pounds per inch

Short Period Frequency - 0.8 c/s
Short Period Damping - 0.4

Friction - 0.2 pounds Pilot No. 1

Acceptable Minus: Noticeable overshoot. No trouble with control system.

Friction - 0.4 pounds Pilot No. 1

Poor Plus: I could track fairly well with this, I think, but it was very frustrating. Low "q" feel and low friction made incidents and magnitudes of inadvertent stick motion high, and the fast short period characteristic of the configuration responded to these undesired motions.

Friction - 1.2 pounds Pilot No. 1

Poor Plus: Rise rate so high that a lot of inadvertent pitch motion accompanied lateral control movement. Friction seemed light; I could feel no assistance in holding near zero control positions.

Friction - 1.3 pounds Pilot No. 1

Acceptable Plus: Not called good only because damping too light. Friction apparent, light; not helpful or objectionable.

Friction - 1.4 pounds Pilot No. 2

Acceptable Minus: Sensitive

Friction - 2.5 pounds Pilot No. 1

Acceptable: Some overshoot. Friction noticeable - I think it helped me hold desired longitudinal control positions.

Friction - 6.0 pounds Pilot No. 1

Poor Minus to Unsatisfactory Plus: Friction heavy, made it difficult to

make small control movements without overshooting, and the airplane dynamics picked up control movement overshoot and caused a lot of undesired pitch. It was bad, but it could be worse.

Short Period Frequency - 0.4 c/s
Short Period Damping - 0.4

Friction - 0.3 pounds Pilot No. 1

Good: No difficulty with the aircraft or controls.

Friction - 0.5 pounds Pilot No. 1

Acceptable Plus: Some overshoot, but it didn't bother me much. Could hardly notice friction.

Friction - 0.8 pounds Pilot No. 1

Acceptable Plus: Some overshoot. Friction noticeable - I think it helped me hold desired longitudinal positions.

Friction - 1.0 pounds Pilot No. 1

Acceptable Plus: Overshoot, but not bad. Friction noticeable but barely; not enough to hold stick at desired positions.

Friction - 1.3 pounds Pilot No. 1

Acceptable Plus: Got some undesired pitch oscillation.

Friction - 2.2 pounds Pilot No. 1

Good Minus: I got some (slight) undesired longitudinal oscillation, but I could track well and had no trouble with it. Could feel some friction; it seemed more helpful than objectionable.

Friction - 2.5 pounds Pilot No. 1

Acceptable Minus: Friction didn't bother me; didn't seem to help either. I didn't seem to do as well as I think I should have been able to.

Friction - 5.4 pounds Pilot No. 1

Poor: Got lots of undesired pitch oscillation. Breakout force caused greater than desired control translation, I think.

Short Period Frequency - 0.2 c/s
Short Period Damping - 0.4

Friction - 0.2 pounds Pilot No. 1

Poor Plus: Hard to track with, pitch rate hard to start then hard to stop. Very easy to move stick.

Friction - 1.2 pounds Pilot No. 1

Poor Minus: Low frequency short period. I could live with it fairly well, though , so it is not unacceptable, though almost. Light friction permitted step type control movements.

Friction - 2.8 pounds Pilot No. 1

Unsatisfactory Plus: As a transport type aircraft, Poor. As a fighter to track this noise, unsatisfactory plus. Main trouble is the frequency of the short period, too low. Friction didn't seem to bother me; I could get quick pulse control movements which seemed desirable for the aircraft dynamics without much trouble.

Friction - 5.3 pounds Pilot No. 1

Unsatisfactory: As a transport type aircraft, Poor Minus. As a fighter employed in tracking this noise, clearly unsatisfactory. Primary complaint is low frequency of short period longitudinal dynamics. Friction seems to make the situation worse.

Control Force Gradient - 10 pounds per inch

Short Period Frequency - 0.8 c/s
Short Period Damping - 0.4

Friction - 1.3 pounds Pilot No. 1

Poor Plus: Not recorded.

Short Period Frequency - 0.4 c/s
Short Period Damping - 0.4

Friction - 0.3 pounds Pilot No. 1

Acceptable: Very light "q" field and friction. Tended toward "finger tip control" which I don't like. I could track, I think, fairly well, but it was an effort.

Friction - 1.3 pounds Pilot No. 1

Acceptable Plus: My primary objection to this was light stick force ("q" feel). If it were damped more heavily, this might not be so noticeable.

Friction - 2.6 pounds Pilot No. 1

Acceptable: Light "q" feel. I got quite a bit of undesired pitch motion.

Short Period Frequency - 0.2 c/s
Short Period Damping - 0.4

Friction - 1.3 pounds Pilot No. 1

Unsatisfactory Plus: Slow response, light forces, "q" feel and friction, led to inadvertent longitudinal stick motion which was manifested in pitch too slowly to permit effective control reversal. As an airplane for straight and level flight, poor.

Friction - 1.4 pounds Pilot No. 2

Acceptable Minus: Stick force was light but sufficient friction was present to damp out unintended longitudinal inputs. Response not best for good tracking (that is, less than adequate).

Investigation of the effects of longitudinal control friction on the pilot-airplane combination in a tracking problem.

Thesis 35763
F24 Faulkner
Investigation of the effects of longitudinal control friction on the pilot-airplane combination in a tracking problem.